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| George                                                                      |                                                                                                 | Salazar      | NASA    |
| M. Natalia                                                                  |                                                                                                 | Russi-Vigoya | KBR     |
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# Human Systems Integration relationships between Deep Space and Deepwater exploration Challenges

George Salazar, NASA JSC., M. Natalia Russi-Vigoya, KBR

## Abstract

NASA pursuit of human missions Beyond Earth Orbit (BEO) to the moon and eventually Mars will pose many new challenges. These missions are characterized by increased risks to human performance due to stress, fatigue, radiation exposure, and isolation. Fundamental changes in spaceflight operations will be required as well. A very critical part of future missions will be assisting the crew with problem-solving and contingency resolution using next-generation smart spacecraft systems. Human Systems Integration (HSI) must be included as part of the systems engineering process. Gateway<sup>1</sup> will serve as part of the proving ground for maturing technology such as autonomous systems and space operations procedures to help meet moon mission goals and prepare humans for missions to Mars. For deep space missions, risk factors affecting humans such as mission duration, distance, and physiological/psychological effects, must be considered. A human is not a simple component but rather a system in a systems-of-systems application—a system influenced by cognitive and biological factors that are difficult to model/analyze. System complexity will demand an integrated approach that requires multiple viewpoints, including the understanding of the astronauts' capabilities and limitations to enhance safety, performance, and satisfaction on the interaction between all system users in a variety of environments to achieve acceptable mission goals and performance. HSI will play a vital role in the development of these future missions. This paper provides a discussion of HSI used at NASA and the critical role human factors engineering will play in the HSI process for future missions along with the challenges. Industries such as oil and gas (O&G) could benefit from the content of this paper to help improve the safety and operations of deepwater/oil and gas exploration activities. NASA engineering and human systems subject-matter expert personnel reviewed challenges reported in space-related environments for long space duration missions and identified similarities with the challenges encountered in deepwater exploration. The researchers noted the space industry's current solutions and proposed a system development view to solve future deepwater exploration challenges using HSI principles. This paper discusses the results of the review.

**Keywords:** Human Systems Integration, Exploration Missions, Human Factors, Systems Engineering, Human-centered Design, Human Performance

## Introduction

NASA pursuit of human missions Beyond Earth Orbit (BEO) to the moon and eventually Mars will pose many new challenges. These missions are characterized by increased risks to human performance due to stress, fatigue, radiation exposure, and isolation. Fundamental changes in spaceflight operations will be required as well. A very critical part of these missions will be assisting the crew with problem-solving and contingency resolution with the aid of what will likely be a next-generation smart spacecraft with various forms of advanced onboard system control and autonomy. Human Systems Integration (HSI) must be included as part of the systems engineering process to ensure the integration and readiness of the technology, the systems, and humans. Gateway<sup>1</sup> will serve as part of the proving ground for maturing technology such as autonomous systems and space operations procedures and prepare for missions to <sup>1</sup>Mars. To ensure mission success and the safety of the crew, risk factors affecting humans such as mission duration, distance, and physiological/psychological effects, must be considered. Systems that deliver and support extended human habitation on the moon will be extremely complex

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<sup>1</sup> Gateway will be the orbiting moon space station

and unique, presenting new opportunities to employ HSI practices in the Artemis<sup>2</sup> Program. Habitation and sustainment for long-duration other world missions will be challenging as NASA only has limited experience— a total of approximately three days, 9 hours on the moon, and supporting low earth-orbiting space stations with frequent resupply of consumables-resupply for deep space missions will be more difficult. Also, the ability of astronauts to cope with spacecraft/habitat information processing demands in the presence of physiological and psychological factors potentially affecting them will be challenging to cope with and still meet system performance.

Since the start of human spaceflight, NASA has placed a high value on the safety, health, and performance of astronauts and its missions. HSI plays an important role in the system development effort-- improvement in factoring the human component into system development. As NASA plans long-duration missions, HSI becomes even more important to address increased system complexity on the human. Through the work of the Human Systems Integration Employee Resource Group (HSI ERG) at NASA, Johnson Space Center, HSI was incorporated into NASA Procedural Requirements (NPR) beginning with the NPR 7123-NASA Systems Engineering Processes and Requirements. The document called out the delivery of an HSI Plan (HSIP) as part of the System Requirements Review documentation (Silva-Martinez, 2016). Subsequently, the NASA/SP-2016 (2007) NASA Systems Engineering Handbook was revised with several updates to the document including material on HSI. Also, to help understand what the role of an HSI practitioner in the NASA systems engineering process is and what HSI processes and activities are involved, an HSI Practitioner's Guide was written and approved (Silva-Martinez et al, 2019).

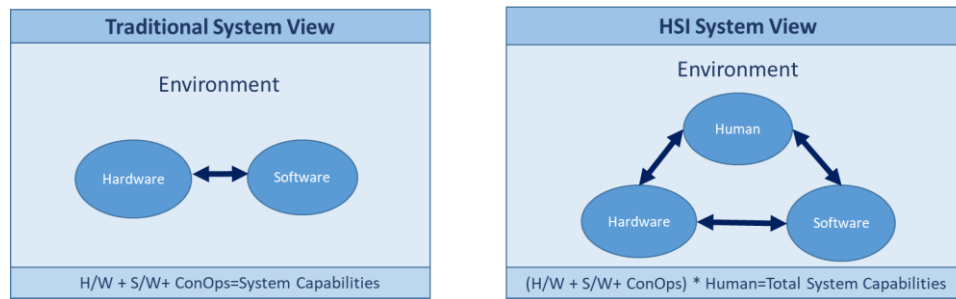
This paper discusses the use of HSI to ensure deep space systems challenges for human spaceflight are addressed. A background of HSI is given followed by a discussion of the known physiological and psychological factors that will affect astronauts. Next, a proposed methodology based on reviewed space exploration challenges reported for long space duration missions and their similarities with the challenges encountered in deepwater exploration is given using HSI principles.

### **NASA Human Systems Integration-Background and Processes**

According to the Human System Integration Practitioner's Guide developed by NASA (November 2015; adapted from INCOSE, 2016), "HSI is defined as the interdisciplinary technical and management processes for integrating human considerations within and across all system elements. It is a robust process in which human capabilities and limitations are effectively and affordably integrated with system design and development. HSI is also an essential enabler to systems engineering practice." In the past, hardware and software were viewed as a system. However, since HSI principles have been adopted, the HSI view sees humans as an imperative part of the traditional system for the whole system development life-cycle (NASA, November 2015; Silva-Martinez et al, 2019). This includes the human capabilities and limitations, supportability and maintenance, habitability, flight and ground operations, training, safety, etc.) Figure 1 depicts these two views.

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<sup>2</sup> Artemis is the moon program that includes the orbiting Gateway, lunar landers, and Orion spacecraft



**Figure 1. Traditional and HSI System Views**

HSI helps in the evaluation of tradeoffs analysis associated with the crew and software and hardware systems. With experts on its six different domains (See Figure 2), HSI helps to enhance the system performance allowing processes, products, and interactions to become more effective and efficient. Researchers (Folds, 2015) have shown that HSI efforts help to address risk and reduce life-cycle costs.

### **The rationale for HSI at NASA**

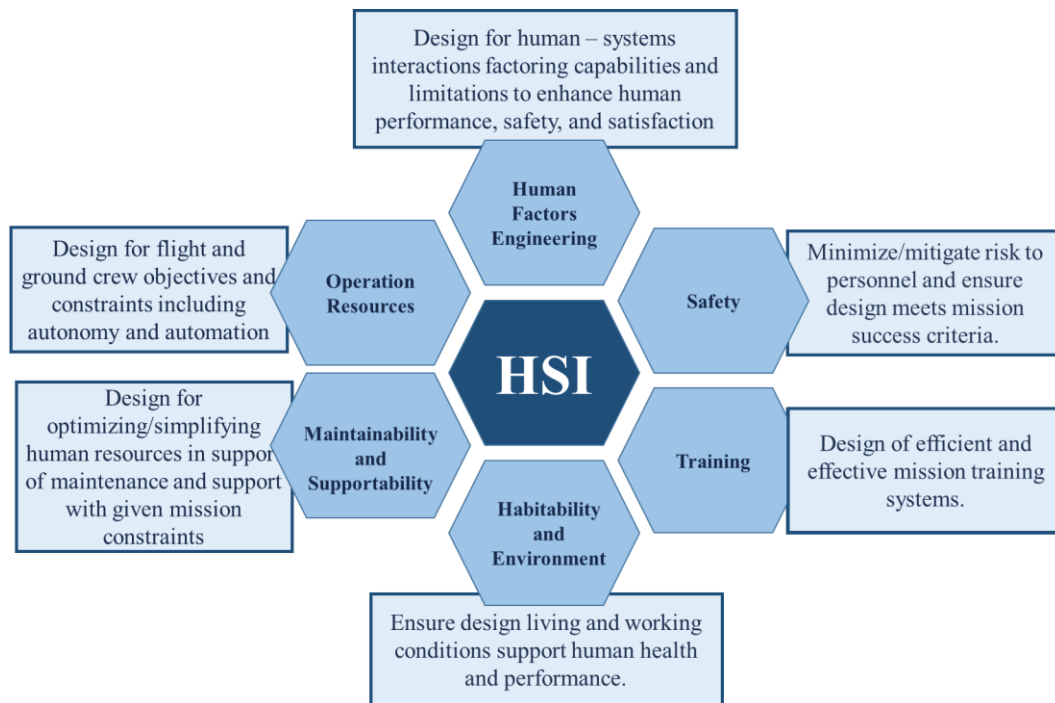
The significant cost and investment in complex human spaceflight missions require NASA to not only build and test highly-reliable systems but to ensure the protection of the health and safety of the crew and ground personnel. This means the space system development considers human needs, capabilities, and limitations. As NASA missions get more complex, HSI technical and management processes ensure that the correct function allocation to human and machine is done, human performance is optimized, and trades are made as part of system development. Activities such as Human-Centered Design (to be discussed later in the paper), provide a methodical method of optimizing systems and increase the safety of operation/maintenance while reducing human error (ISO, 2010). Both the total system performance (human + system + environment) and ownership cost in complex system development can only be fully recognized and achieved when the human element is factored in.

With projects becoming more complex, keeping operations and maintenance costs low after deployment will be challenging. As Walde et al., (2015) recognized, about 70 percent of the lifecycle cost of the program is committed early in the project. Walde et al., (2015) suggested that early decisions without good analysis that factors the human are critical. In addition, as noted by the authors, the cost to make changes increases exponentially over time. An example from NASA is the Space Shuttle program that was sold as a low earth orbit transport vehicle that operated much like an airliner. Very little effort was spent on the operations of the vehicle and more on the Design, Development, Test, and Evaluation of it. Consequently, what should have been a vehicle that only required fewer than 50 people to operate and turn around time in weeks came to be a massive operations effort requiring over 25,000 workers to and months to process the vehicle (NASA, November 2015).

### **HSI and NASA Systems Engineering Process**

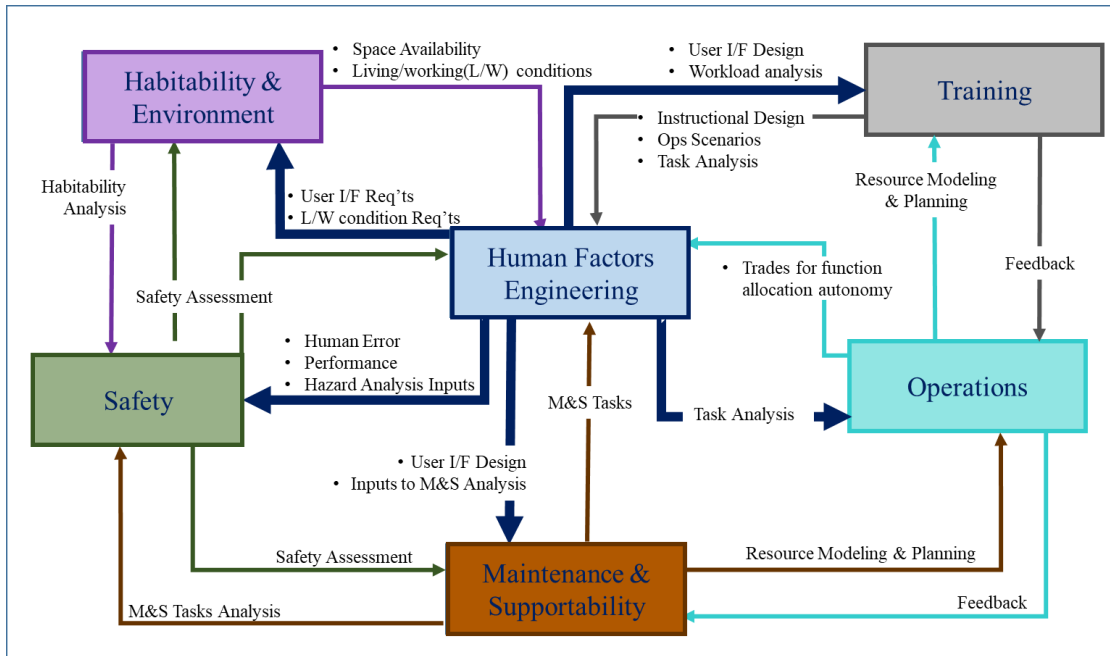
HSI is part of NASA's system engineering discipline (NASA, November 2015) that applies knowledge of human capabilities and limitations throughout the design, implementation, and operation of hardware and software. HSI requires the integration of multiple technical processes and therefore tends to ensure a system is not developed in silos. The goal of HSI is to ensure that the human/system integration is carefully considered and planned from the outset of any program or project.

Figure 3 shows the HSI domains defined by NASA. Unlike the DOD, the NASA HSI domains do not include Manpower and Personnel. The NASA HSI domains are also less focused on the large workforce, and diverse skill sets required for DoD mission objectives. Instead, the focus is on habitability, system safety, reliability, and usability/human error concerns, which are critical for crew safety and mission success. At the center of the HSI activities and interactions is human factors engineering (HFE).



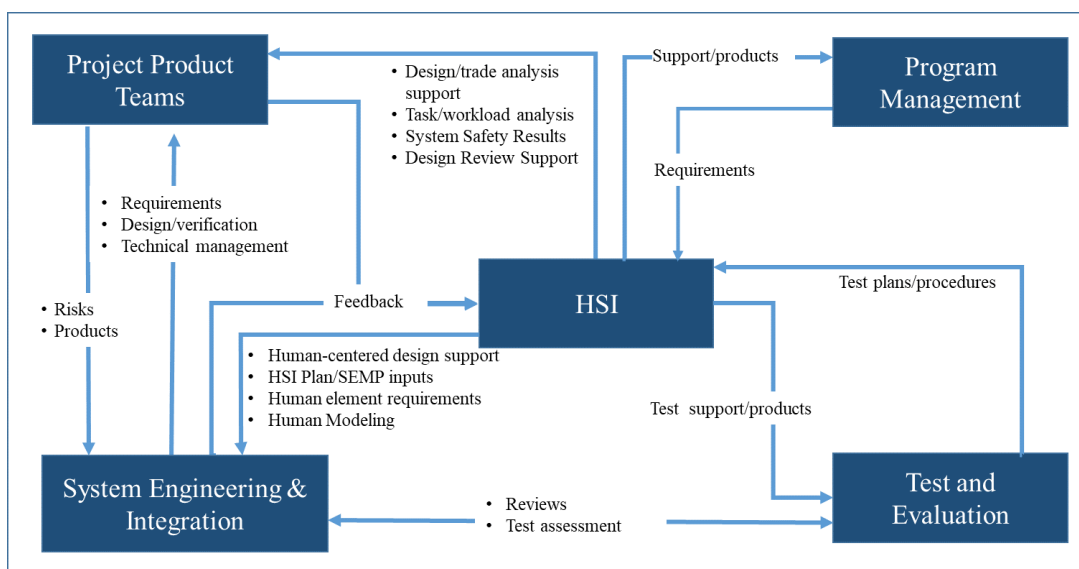
**Figure 2. NASA HSI Domains**

As Figure 4 indicates, there is a considerable amount of interaction between the various HSI domains exchanging data. For example, the Maintenance and Supportability domain sends tasks data to human factors engineering for HFE to assess the interaction of the user interface (I/F) design. Training sends its operations task scenarios and tasks to HFE for user I/F analysis and workload. HFE is also heavily involved with crew training and assessment of interfaces associated with the spacecraft/habitats—particularly early on the project. HFE, along with safety, ensures that system safety is addressed and human error is eliminated or mitigated.



**Figure 4. Notional HSI Domain Interaction**

Figure 5 shows a notional interaction between HSI and external interfaces such as program management and systems engineering. HSI processes use systems engineering processes to ensure that all human-related technical issues are properly identified and addressed during planning, design, development, and evaluation of technical systems (Folds, 2015). Test and evaluation were broken out to show HSI support for much of the crew human-in-the-loop testing—for both evaluation and “run-for-the-record verification and validation testing. Project product teams include the HSI practitioner that ensures the human is considered in all aspects of the design. Major interaction occurs with system engineering and integration (SEI) as requirements engineering (development and management) occurs throughout the life-cycle and risks are identified and assessed such as hardware, software, and integration. A significant interaction between HSI, test & evaluation, and SEI is human-centered (HCD) design activities.



**Figure 5. Notional HSI and External Interface Interaction**

Critical to the systems engineering (SE) effort is the human-centered design (HCD). HCD is a methodology used to ensure that a design accommodates human capabilities and limitations. Its use is in the development of interactive systems that focus on making systems usable by ensuring that the needs, abilities, and limitations of the human user are met. It's a multidisciplinary activity involving a range of skills and stakeholders who collaborate on the design. Most importantly, HCD is an iterative activity that intentionally uses data gathered from the users of the system and evaluations to update the design. Mission success is optimized when attention is paid to human interfaces that provide operational clarity and consistency and reduce the potential for human error, performance failure, or injury. Figure 6 shows the HCD process. As shown, the key outcome of the process is to optimize performance, reduce cost, and minimize risks. HSI Planning and Context-of-use and environment serve as part of the SE definition and analysis activities. Design solutions are part of the SE design. In addition, the evaluation design solutions activities are part of SE hardware and software design efforts as well as verification and validation activities.

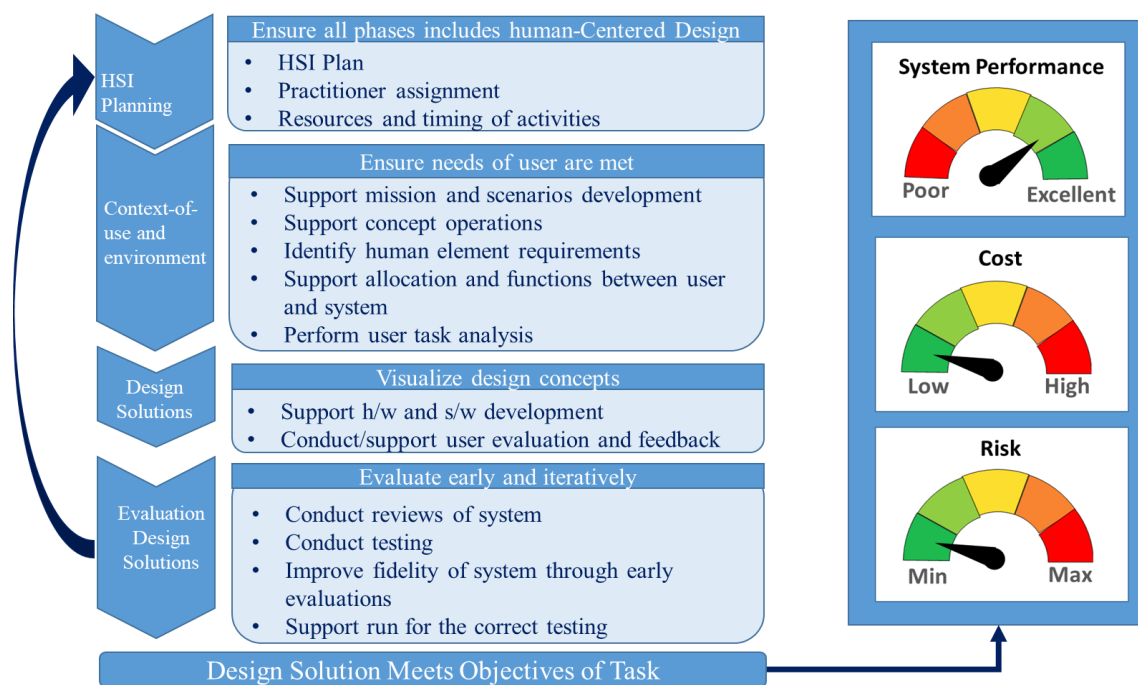


Figure 6. Human-Centered Design Process

User satisfaction is increased by involving the user in the HCD process so that users understand and participate in design decisions. This is especially important when the user has critical control responsibilities over the system or when user interaction is important to mission goals. NASA will definitely learn a lot from applying HSI to the moon missions and improve the process for Mars missions. With the background given on NASA's use of HSI in programs and project, next is a discussion of how HSI principles, as used by NASA for future deep space missions, could aid the oil & gas/deepwater industry.

## Methodology

NASA engineering and human systems subject-matter expert personnel reviewed challenges reported in space-related environments for long space duration missions and identified similarities with the challenges

encountered in deepwater exploration. The researchers noted the space industry's current solutions and proposed a system development view to solve future deepwater exploration challenges using HSI principles.

## Results

The following are identified HSI relationships between Deep Space and Deepwater Exploration Challenges:

a. Isolation and confinement: Isolation and confinement are factors that can significantly affect the human mind and body. Research has shown that isolation can create neurocognitive changes, fatigue, misaligned circadian rhythm, sleep disorders, altered stress hormone levels, and immune-modulatory changes (Pagel & Choukèr, 2016). In the deepwater/oil and gas industry, operators normally encounter confined environments in maintenance and sampling operations. Isolation and confinement issues can be aggravating when the surrounding environmental factors and criticality of the task(s) put more pressure on the human –potentially resulting in the more likelihood of human error. Like deep space long-duration missions, future deepwater operations may demand longer stays on the rig resulting in facing greater isolation in these confined environments and possibly increasing the risk of human error.

The way that NASA has faced this issue has been with specialized crew training. The crew skills are important, but it is also important to know that the crew will get along together. Therefore, NASA selects the crew for a mission very carefully-factoring many psychological factors beyond the scope of this paper to explain (Slack, Williams, Schneiderman, Whitmire, & Picano, 2016). In addition, NASA monitors, detects, and addresses early crew interaction risk factors-particularly during evaluation and training. Since prolonged isolation can have serious effects on humans, future smart systems should be designed to support the human system interaction under isolation and confinement. For example, a machine-learning system would understand when the crewperson is no longer able to control a critical situation like fire and would take over the task.

b. Long-distance: Both crew and operators in deep space missions are restricted by the distance to their natural environments. Operations in deep-sea environments restrict the distance from dried land and crewmembers are restricted by the distance from the earth. This restriction limits their ability to quickly come back to get the materials they need from their natural environment. In addition, to be isolated and confined, future exploratory missions in the sea or deep space, smart systems are expected to help decide on the planning and accessibility for the storage and retrieval of additional supplies and medical supplies, and communications to the crew to aid in logistics decision making. Mission logistics planning will be critical for mission success as the long-distance travel time from Earth to Mars will take months to get what is needed to complete the task. What has helped the crew in current space missions is appropriate planning and the ability to prepare for self-sufficiency. Future mission's operators and crew need to be equipped with smart systems that facilitate planning and product development, allocation, and task execution. Deepwater programs could benefit from the use of long duration logistics planning.

c. Gravity fields: Human deep-sea exploration and space exploration have a lot in common. Spacecrafts are designed to enhance human life beyond earth and submarines are designed to enhance life beyond dry land, so crewmembers can breathe and work inside the vehicles during deep missions. Both deep space explorers and deep water explore the use of robotics to explore places for which the human capabilities have not been expanded. These environments make the design of the human-computer interface to control the vehicles important for mission success. Equally important is the habitat/vehicle layout as well. At NASA, crewmembers practice extravehicular activities underwater on life-sized models. NASA has a Space Vehicle Mock-up Facility (SVMF) dedicated to crew training. Future deep

space and water exploration will require more research on environmental changes that affect the different environmental fields.

For example, in deepwater exploration, the deeper you go under the sea, the greater the pressure of the water pushing down on you. The longer you stay in the water, your body is exposed to various physical and mental stressors. The farther you go on space, you encountered different gravitational fields that also affect your body and mind. NASA has identified that transitioning from gravity fields has bone and muscle density effects, and your body encounters internal fluids pressure (Abadie, Lloyd, & Shelhamer, 2019). This is one of the reasons why a simple activity as walking becomes more challenging after coming back from these environmental fields. Thinking in the future, and the possibility to expand the terrestrial capabilities, it is important to understand how technologies can help us to adapt and quickly recover from the different gravitational field. Currently, NASA monitor and treat changes in the human body. NASA is working on ways to aid deficiencies and body limitations with equipment or/and medicines. There are exercise times required for the crew and fitness evaluation. There is also a team of people focusing on crew nutrition and fine motor testing. However, as we go deeper into water or space, there is a need for more research to learn how to enhance the capabilities and aid the limitations of the human body.

d. Hazards hard to perceive: Despite all the hazard analysis and failure modes and effects analysis, deep exploration missions could encounter hazardous environments that are not easy to see. For instance, carbon dioxide (CO<sub>2</sub>) is emitted by different technologies and when air is recycled and there is not a good airflow, it can present tremendous hazards for the crew or deepwater/oil and gas operators in confined areas such as a sub. Future smart habitats need to improve the way they integrate the habitat technologies and identify means to mitigate or avoid these hazards. In the International Space Station (ISS), a fan allows the air to keep moving which reduces the increment or builds up CO<sub>2</sub>. Radiation is also not easy to see either. Crewmembers can encounter very high radiation environments in future missions. This is worrisome because even though we are all exposed to some levels of radiation, high levels of radiation and generate cognitive and physical problems. NASA (Rask, Vercoutere, Krause, & Navarro, 2008) has identified different types of protective shielding. Earth has a natural protective magnetic field (LEO), and some natural resources can serve as radiation shields (e.g., water; Rask et al., 2008). The dose of radiation exposure is measured in accordance with the U.S. National Academy of Sciences Space Science Board and the U.S. National Council on Radiation Protection and Measurements (NASA, 2009). NASA has also identified alarms to communicate those hazards. Future exploration missions have to continuously identify ways to prevent or mitigate hazardous environments that are not easily seen. Another approach as used by NASA is to train as much as possible in the anticipated environment to identify potential risks not caught during a hazard analysis.

e. Hostile or closed environments: Both crew and deepwater operators will encounter hostile environments in deep space/deepwater exploration. There are changes in temperature, oxygen, pressure, lighting, the quantity of space, and in some cases levels of noise. Cameron (2012) explained multiple risks from deep-sea expeditions. For example, the risk of freezing when the system in place does not work and you must correct the issue a challenging environment and clothing that is difficult to work in.. Crew members depend on life support systems. NASA manages those environments with the development of highly-reliable life-support systems and strategic planning of food, sleep, and exercise. They constantly monitor the environments and recycle resources as much as possible. Continuously learning from new environments will help industries to develop technologies that allow them to explorer deeper in waters and further into space. Training in simulated/actual hostile environments is important for the crew to prepare for off-nominal events.

f. Operations paradigms: Communication and expertise sharing have been a very important factor in space mission success. Currently, submarines in autonomous missions can carry up to 155 people and deepwater rigs can have more than 25 people operating in an autonomous mode as well. Everyone has a role and they all work together to resolve anomalies. Deep-sea exploration gets easier when there is a body of knowledge that is always there to help in the resolution of unexpected situations. Currently, Mission Control (MC) has many flight controllers who are highly trained to support ISS. However, future missions will lack spacecraft/habitat to Earth communications. Communication interference and delays in communication are expected as we get to places that we have not visited before. Therefore, future smart systems for exploration need to prepare for autonomous missions with smarter integrated technologies. Recent research at NASA (Vera, Holden, Russi-Vigoya, Dempsey, & Wu, 2019; Holden, Russi-Vigoya, Adelstein, Cross, & Munson, 2019) has shown there is a need to develop advanced training systems, intelligent information systems, problem-solving aids, and design for autonomy in space future missions. The key challenge is to ensure that the crew can understand the dynamic state of the system and make appropriate decisions. The Human Research Program is designating efforts for research in Human Capabilities Assessment for autonomous Missions (HCAAM). Much of this research could benefit deepwater/oil&gas industries too.

g. Human and machine complexity: For deep space missions, the lack of closed-loop communication in some circumstances, will require helping the space crew in communicating with the earth as effectively as possible when they need to, but also having autonomy available to aid the crew as much as possible is desired. This may require the passing system state information continuously to mission control-something ordinarily not done for ISS operations. Future deepwater applications may involve more automation and autonomy to reduce the likelihood of human error. However, caution in implementing automation and autonomy with the human is important. If not designed correctly, automation and autonomy can result in machine/mode confusion making it difficult for a human operator to take over in the event of an imminent failure of the system (Leveson, 2011). The importance of implementing HCD early on is important to flesh out potential issues in the design and training difficulties.

h. Iterative system maturity innovation and adaptation: Due to the number of unique human space missions NASA will do and the complexity of mission tasks and operations, HSI processes cannot follow a waterfall approach. The HSI process used for one mission cannot completely be used in other exploration mission-tasks and operations may be different. However, it is important to learn from the current HSI process to optimize resources, optimize opportunities for improvement, and evolve in design. Iterative system development and space exploration missions have a lot in common. Uncertainty is definitively part of the equation. However, continuously learning from the initial planning until the deployment stage will help the system to mature, enhance innovation, and improve human adaptation to new environments. As previously shown in figures 4 and 5, the HSI process for the six domains is iterative as well as the HSI/systems engineering interaction. A key HSI process is the HCD as shown in figure 6 that should begin early in the development cycle to flesh out requirements, the concept of operations, and design solutions. This leads to a cost-effective solution that buys down project risks and maximizes system performance. Like unique space missions, deepwater project varies depending on what the objective is and the location of the deepwater site.

i. Human System Integration design: The design must enhance human capabilities and aid human limitations. From the first stages of the design process, think about the way the human interacts with the system and system components. Try to aim for effective, efficient, usable, and safe interactions. Systems

have different levels of autonomy. Human system integration must evaluate all levels of autonomies. The simplicity of the systems is going to help smart autonomous systems interactions to be successful. It is important to identify objective ways to measure user interactions. Good HSI system design metrics can optimize savings, time, and uses of resources. Plan for several evaluations of the design early on to identify ways to measure user-task interactions and see if interactions are improving cognitive and physical capabilities, performance, and safety. For the inclusion of autonomous systems development, human interaction and command and control of the system should be considered at every phase of the system design and development. Architecture design, mission design, vehicle design phases play a key role starting with the architecture design.

j. All HSI domains considered in the development process: As part of the HSI effort, it's important that all domains are addressed that affect the human—including the environment. The HSI plan should spell out how the assessment of what domains affecting the human apply and which don't. As the complexity of the human-machine interface and crew interaction increases, so does the risk of human error and the potential disasters that can result. For NASA, the six domains shown in figure 3 must be considered to ensure mission objectives are met, and the potential of human-machine/human-task errors that could occur in each of these domains is mitigated/reduced.

k. Risks: HSI risks analysis should be considered at the same level of importance as the risks that specific hardware or software functions cannot meet the required technical specifications. Each of the domain subject matter experts should identify risks that should be part of the overall systems engineering risk management process. Early assessments of habitability, sustainment/maintenance, operations, training, and safety by human factor engineering can identify risks that require tracking. This may lead to ensuring that the training facilities and simulators are as close to the actual systems used in the environment the systems will be used in. Hazard analysis of critical requirements such as control for human error should provide an early assessment of potential risks that need to be assessed, such as inadvertent activation of critical functions. For human-computer Interface risks, early usability assessment provides an opportunity to reduce the hazard and risk of the interface. For NASA, hazard analysis provides an early indication of where potential hazards in a mission can occur and what controls can be put in place to mitigate them. This leads to verification/validation testing events in the realistic environment using actual systems to be used that show hazard controls are in place in the design. (A motto at NASA is “Test as you fly. Fly as you test”)

l. Organizational culture: Organizational culture play a vital role in implementing HSI. It can directly influence system performance through rigid compliance with rules and policies or indirectly hinder it through resistance to comply with new methods or technology (Pew & Mavor,2007). Leadership commitment to HSI is demonstrated through actions and policies, such as ensuring collaboration with all HSI domains is integrated and not siloed as well as adequate resources are provided to support HSI objectives. The priority of human-centered design is evident in the culture. It's important that the organization fosters innovation with multidisciplinary teams and support teams and individuals to grow and learn continuously. Allow “lessons learned” to be opportunities to grow and move forward. Exploration missions have shown ways that have worked for years, as technologies evolve, organizations need to be alert to new paths and ways that optimize human-machine/human-task interactions.

## Conclusions

Human System Integration (HSI) has shown to enhance safety, health, and performance of human spaceflight missions while reducing program lifecycle costs. The process begins during initial capability definition and requirements capture, through design and manufacturing, and through deployment. Currently, there are many systems challenges for future deep space exploration missions that can relate to deep water missions. Some of these challenges are isolation and confinement, distance from the crew or operator natural environment, gravitational fields, hazards hard to perceive, hostile or closed environments, and operations paradigms. Some approaches to those challenges using HSI principles were discussed. Future exploration missions need to have iterative system maturity innovation and adaptation, HSI embedded into the system design at all levels and support from the organization culture is important to ensuring successful missions, reducing lifecycle costs while maintaining the safety of the human operating complex systems.

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